fast-scan cyclic voltammetry, the authors could measure 100-millisecond pulses of dopamine — in the past, only minute-to-minute changes had been studied.

Phillips *et al.* found that a brief dopamine pulse was released just a few seconds before the animals became interested in approaching and pressing a lever that delivered cocaine injections. (This pulse is thought to be triggered by the context of the drug-associated test chamber, a pavlovian association.) Dopamine levels continued to increase during the final approach to the lever, and peaked just a few seconds after the lever press, while the cocaine injection and an audiovisual cue were delivered simultaneously. In animals that had learned to associate the audiovisual cue with cocaine, the cue itself caused a rapid increase in dopamine levels for several seconds (Fig. 1), even when it was presented in the absence of lever pressing or cocaine injections. This did not occur in animals that had never learned to associate the cue with cocaine. Finally, electrical stimulation of dopamine-producing neurons triggered a drug-seeking response — rats approached and pressed the lever.

These findings suggest that naturally evoked dopamine pulses are involved in both triggering and pursuit of reward-seeking behaviour, and that environmental cues (here, the test chamber or the audiovisual cue) use this mechanism to prime such behaviour. Previous studies detected prolonged increases in dopamine levels that lasted for several minutes following a drug reward. But drug-seeking behaviour ceases during these large, post-injection dopamine increases. Moreover, such studies generated mixed, and even contradictory, findings regarding events that happen before the drug reward is received. Phillips *et al.*[4] suggest that subsecond dopamine pulses are released only when drug-induced dopamine levels fall below a certain threshold. Similarly, they propose that environmental cues trigger reward seeking only when this subsecond regulation of dopamine pulses is possible.

It seems that dopamine represents both the chicken and the egg in the events underlying behavioural reinforcement. Dopamine acts as a reward for behaviour that precedes its release, and subsequently it triggers pursuit of the same reward after its release. As a rat chases its tail, so drug addicts may suffer a similar vicious circle of priming and reward controlled by these dopamine signals. Therapies aimed at preventing one or both of these signals could be effective treatments for addiction. ■

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Atomic physics

A new spin on magnetometry

Dmitry Budker

The capability to measure small, localized magnetic fields is valuable in biology as well as physics. A new device, based on spin-polarized alkali atoms, achieves better sensitivity and resolution than before.

On page 596 of this issue, I. K. Kominis and colleagues[1] report on a new type of atomic magnetometer that achieves unparalleled sensitivity to small magnetic fields as well as millimetre-scale spatial resolution. This device may open up exciting frontiers in diverse areas of science, ranging from biomagnetic imaging to testing fundamental symmetries of nature.

The most sensitive magnetometers of this type use vapours of alkali atoms, such as potassium, that have a single unpaired electron. When the atoms are subject to a beam of resonant, polarized light (such as from a laser), these unpaired electrons are excited to a higher energy level, but subsequently return to their ground state by spontaneously emitting the energy or losing it through collisions. This 'pumping' process transfers the polarization of the incoming light to the atoms, affecting the direction of their electronic spins. But imparting polarization to the atoms like this, in turn, modifies the optical properties of the atomic medium; for example, it changes the way it absorbs laser light. The sensitivity of such a system to an external magnetic field comes from the torque that the field exerts on the magnetic moments of the atoms, which are themselves proportional to the electron spin.

In 'all-optical' magnetometers, such as the one developed by Kominis *et al.*[1], detecting an external magnetic field can be thought of as a three-stage process (Fig. 1) — although, in fact, all three stages may occur simultaneously. First, the atoms are optically pumped and adopt the polarization of the pumping laser beam. Second, the magnetic field to be measured causes the atomic polarization to evolve: in the simplest case, the atomic magnetic moment precesses around the direction of the magnetic field. Finally, the evolution of the polarization is probed using laser light — either from the same laser beam that produced the pumping, or from a separate source (as it is in Kominis and colleagues' set-up).

According to the laws of quantum mechanics (namely, the uncertainty principle), for a given time-duration of the measurement, the intrinsic sensitivity to magnetic fields is inversely proportional to a product of three quantities. These are the magnetic moment of the atoms, the square root of the number of atoms involved in the measurement and the square root of the spin-relaxation time — that is, the length of time for which polarized atoms maintain their polarization in the absence of pumping. So, to improve the sensitivity beyond levels already achieved in other devices (which, for a measurement lasting one second, is at best about 1 femtotesla — 1 fT = 10^{-15} T), the number of atoms in the system and their spin-relaxation time should be maximized.

There are several mechanisms that limit spin-relaxation time, one of the most important being depolarization caused by collisions with the cell walls that enclose the atomic vapour. The best way to get long spin-relaxation times has been to use vapour cells whose inner walls are coated with paraffin. An atom can bounce many thousands of times against a paraffin-coated wall before becoming depolarized; relaxation times are of the order of a second for a cell that is 10 cm in diameter. The atom density inside such cells, however, is usually relatively low, fewer than 10^{10} atoms per cubic centimetre: at higher densities the spin-relaxation time decreases because of spin-exchange collisions between the alkali atoms.

In a spin-exchange collision, the electron spins of the colliding atoms rotate with respect to their combined spin, which is conserved in the collision. All alkali atoms have non-zero nuclear spin, I, and their ground states are split into two 'hyperfine-structure' components, characterized by the total angular momentum $F = I \pm 1/2$. The direction of magnetic precession, determined by the relative orientation of the electron spin with respect to the total angular momentum, is opposite for the two hyperfine states. Thus, in the presence of a magnetic field, the spin-exchange collisions that randomly transfer atoms between these states normally lead to spin-relaxation, as atomic spins

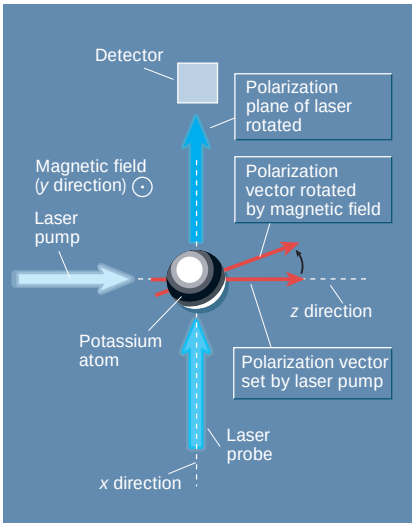

Figure 1 **An 'all-optical' magnetometer. Potassium atoms are optically pumped by a laser beam, taking on its polarization. The presence of a magnetic field (in the *y* direction, out of the plane of the page) deflects the atoms' polarization vector. A second laser beam — the 'probe' — picks up this deflection, as its own polarization plane is rotated. Detecting this effect on the polarization of the laser probe gives a sensitive measure of the magnetic field strength. In the device developed by Kominis *et al.*[1], sensitivity to fields below 10^{-15} T has already been achieved, and 10^{-18} T could be reached.**

acquire random angles with respect to each other.

Kominis *et al.*[1] have overcome the limitation due to spin exchange, and maintain an alkali-atom density in the vapour cell that is about 10,000 times higher than before — without any substantial degradation of the relaxation time. The idea (which goes back to the work of William Happer and colleagues in the 1970s) is that if the rate of spin-exchange collisions significantly exceeds that of the magnetic precession, the spin-exchange relaxation is effectively turned off. In this rapid spin-exchange regime, we may no longer speak of magnetic precession of atoms in an individual hyperfine state. Instead, each atom experiences an average precession in the same direction as would a free atom in the $F = I \pm 1/2$ state. This is because atoms, while being redistributed among the sublevels, spend more time in this state, which has a higher statistical weight and higher electron-spin polarization. As a result, in a weak external magnetic field, the average angular momentum of the atomic vapour precesses without spin-exchange relaxation (although at a slightly slower rate than free atoms).

To reduce spin-relaxation on the cell walls, instead of using an anti-relaxation wall coating Kominis *et al.* add a dense helium buffer gas (at a pressure of several atmospheres) to the alkali-atom vapour cell. The presence of the buffer gas slows down the diffusion of the alkali atoms. This, combined with spatially resolved optical detection, means that localized magnetic-field measurements can be made.

This magnetometer seems ideal for biomagnetic imaging, particularly for recording electromagnetic activity in the brain. Optical-pumping magnetometers have been used successfully in the past to map the activity of the heart, which produces fields of the order of 10^{-10} T (see, for example, ref. 2). But brain imaging is more challenging because the magnetic fields in the brain are at least a thousand times weaker. The new device can detect a magnetic field as small as 0.5 fT, pinpointed to within 2 mm. And Kominis *et al.* claim that both the sensitivity and resolution could be improved with further development of the magnetometer — the magnetic-field sensitivity could even reach 10^{-18} T.

It is also interesting to note a related development: Kornack and Romalis[3] (co-authors of Kominis *et al.*[1]) have demonstrated a more unusual 'magnetometer' — designed to be completely insensitive to magnetic fields. In the vapour cell of this device, the buffer gas is another isotope of helium, ^{3}He, which becomes spin-polarized through spin exchange with the optically pumped potassium atoms. The polarized helium picks up variations in the external magnetic field and automatically compensates for their effect on the potassium atoms, through the effective magnetic field that arises from spin-exchange interactions between the two. Instead of measuring a magnetic field, the aim here is to be sensitive to hypothetical interactions that might arise from any failure (or violation) of the fundamental symmetries of physics, such as Lorentz invariance, which holds that the laws of physics are the same for all observers independent of their positions and uniform motion in space.

This and the work of Kominis *et al.*[1] continue a productive tradition in atomic physics of synergy between fundamental and applied science. ■

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Nitrogen cycle

Solution to a marine mystery

Allan H. Devol

The anammox reaction, a microbial process that was first observed in waste-water treatment plants, looks as if it may be a key player in the nitrogen cycle in certain parts of the oceans.

In the oceans, denitrification is the process by which nitrate (primarily) is reduced to N_2 — inert dinitrogen gas. It occurs when certain bacteria decompose organic matter in environments where oxygen concentrations are vanishingly low, and is how 'fixed' nitrogen is converted into a form that cannot be used by most marine plants. This was believed to be the only mechanism of N_2 production in the oceans — and so by far the largest marine sink for fixed nitrogen.

On pages 606 and 608 of this issue, however, Dalsgaard *et al.*[1] and Kuypers *et al.*[2] show that large-scale conversion of fixed nitrogen to N_2 is probably occurring through another route. They find that N_2 can be produced by the anaerobic oxidation of ammonia in the oceanic water column, and that this 'anammox reaction' may be common in natural marine environments. Although there was evidence that the anammox reaction occurs in marine sediments[3], the new findings enlarge the picture and could significantly alter our understanding of nitrogen cycling in the ocean. Denitrification is balanced by nitrogen fixation, which is carried out in surface waters by highly specialized organisms that can reduce N_2 for incorporation into organic tissue. The balance between the two processes is such that, over vast areas, plant productivity in the oceans is limited by the amount of fixed nitrogen[4]. So the details of denitrification and nitrogen fixation are very important.

In the upper, sunlit layer of the oceans, photosynthetic organisms produce organic matter in the proportion carbon:nitrogen:phosphorus of about 106:16:1. This is the Redfield ratio. When this organic matter sinks out of the sunlit layer and is decomposed, carbon dioxide, ammonia and phosphate increase in the same ratio. In oxygenated marine environments, the regenerated ammonia is oxidized to nitrate. But in oxygen-deficient environments, decomposition continues via denitrification, and nitrate concentrations begin to decrease while those of phosphate continue to increase. Oceanographers can estimate the amount of denitrification that has taken place from the difference between the amount of regenerated nitrate predicted